PISCES: Developing New Design, Materials and Technologies for Sustained Human Presence on the Moon and Mars

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Abstract

PISCES, the Pacific International Space Center for Exploration Systems, is being developed on the Big Island of Hawaii as an integrated research facility and simulated lunar settlement for the purpose of developing new technologies needed for a sustained human presence on the Moon and Mars. PISCES was created by the University of Hawaii under the auspices of the Japan-US Science, Technology and Space Applications Program (JUSTSAP), and has recently been funded by the State of Hawaii through the Department of Business, Economic Development and Tourism (DBEDT). This new center will be built on partnerships between industry, academia and the governments of spacefaring nations, adopting a model that has seen wide success in such programs as the NASA Research Partnership Centers (RPCs), the NASA Robotic Engineering Consortium at Carnegie Mellon University, and numerous programs within NIST, the Department of Commerce and the National Science Foundation. In addition to its research and development mission, PISCES will function as an education, research and technology development center; a training center for astronauts, scientists, K-12 and university students; and a public outreach resource for local residents and tourists to experience the multitude of scientific, educational and economic benefits that space exploration could bring to Hawaii. New technologies developed in PISCES and at universities and industries around the world will require testing in an environment simulating as closely as possible that found on the Moon. Several nations plan robotic exploration missions to the Moon in the next few years, and PISCES will be an important proving ground for hardware developed through collaborative projects in science and technology. To validate space operations, new system architectures, designs, materials and mechanisms had to be developed, such as a robotic vehicle called ATHLETE (the All-Terrain Hex-Limbed, Extra-Terrestrial Explorer), and materials had to be utilized from space. This ATHLETE vehicle concept is capable of efficient rolling mobility on moderate terrain and walking mobility on extreme terrain. Each limb has a quick-disconnect tool adapter and associated tools so that it can perform general-purpose handling, drilling, scooping, assembly, maintenance and servicing tasks using any or all of the limbs. Each of ATHLETE's 6-degree freedom limbs is equipped with non-pneumatic, lunar-appropriate, compliant wheels to enable rolling mobility in soft soil. Also, new ISRU materials and designs had to be developed to accommodate the space environment to sustain human settlements, deal with moon dust, and ensure very long-duration operations. Astronauts embarking on exploration missions and long stays on the Moon will need training in the use of these new technologies to free themselves from the drudgery of routine chores and to increase their time for scientific and technological achievements. This paper describes the PISCES development plans, particularly in the areas of *In-Situ* Resource Utilization, Robotics and Education and Outreach.

Keywords: Integrated Research Facility, Collaborative Projects in Science and Technology

1. Introduction

The Pacific International Center for Space Exploration Systems (PISCES) was established at the University of Hawaii at Hilo with some funding from the State of Hawaii Legislature through Senate Bill 907. The vision of PISCES is a comprehensive, international research and education center dedicated to the development of technologies needed to sustain human life on the Moon and beyond. Its mission is to advance the settlement of space through partnerships with industry, academia, NASA and other governmental space agencies. PISCES will feature a simulated lunar outpost and other testing sites located on the volcanic terrain of the Island of Hawaii. Areas of emphasis at PISCES include *In-Situ* Resource Utilization (ISRU), Robotics, Habitation, Education and Outreach. The benefits of PISCES include enhancement of educational institutions such as UH-Hilo, job creation, inspiration of young people to pursue education in the Science, Technology, Education and Math (STEM) disciplines, and general economic development through secondary businesses and spin-off industries.

The PISCES Development Plan calls for a 10-year development period, during which time State funding will grow for the first two years and then phase out after five years, when the center is expected to be self-supporting through a combination of funding from NASA and other space agencies, industry, universities and private donors. PISCES has had great success in matching State funding to date in its first year. After just five months of operation, two NASA proposals were funded for work to be done with and at PISCES, for a total of $600K. Thus, at this writing, PISCES has more than matched the first year's funding from the State, and additional external funding could be forthcoming before the year is out. In addition to securing matching funds, PISCES has accomplished many of the goals laid out in the original proposal to the State of Hawaii and its other stakeholders.

2. Near-Term Goals and Objectives of PISCES

The PISCES program for fiscal year 2008-09 will allow the initial successes of the PISCES program to be expanded and solidified, while implementing key elements of the development plan that was submitted with last year's original proposal. Major tasks will include:

a) <u>Strengthening the management and staffing of PISCES</u>. At the management level, the current organization will evolve from the current mostly volunteer group into a solid organization as defined in the organizational plan developed in FY 2007-08. Members of the Board of Directors will be selected who can both guide the development of PISCES as well as serve as additional conduits to external stakeholders. The management plan for PISCES will be strengthened. The process by which the people responsible for each of the functional areas turn their plans into approved and funded projects will continue to be developed. The PISCES organization chart is shown in Figure 1. Consistent with the specifications of its creation as a Center at the University of Hawaii at Hilo, PISCES will continue to have as its Deputy Director a tenured member of the Department of Physics and Astronomy.

b) <u>Expanding PISCES involvement at the University of Hawaii</u>. PISCES had its genesis in the Department of Physics and Astronomy at the University of Hawaii at Hilo and will remain anchored in that department. However, just as it will be necessary to involve a multitude of disciplines at a future lunar outpost, it is important to include in PISCES individual faculty members and their students from a wide variety of disciplines, beginning with UHH and expanding to UH-Manoa and other partnering universities in order to bring in the most appropriate individuals at each institution. Efforts to accomplish this in FY 2008-09 will concentrate on the departments of Geology, Biology, Sociology and Hawaiian Studies at UHH through "buyouts," whereby individual faculty members are relieved of some of their course loads to develop plans for relevant research and education projects at PISCES. PISCES supports efforts to create an engineering department at the University of Hawaii, Hilo, to create the next generation of scientists and technologists that can provide the professional leadership for the future of the state.

c) <u>Providing valuable lessons to PISCES in FY 2008 on how to set up and support future field tests</u>. This will include developing the personal interfaces with the community that will be required to define, characterize and gain approval for the use of sites and understanding the infrastructure required for the support of field tests and the level of PISCES support that is required for field tests. This

will enable more precise estimates of costs and schedules that can be associated with future partnership agreements with potential users of PISCES test sites. The IPP field tests contracts won will be conducted with a combination of funding from NASA and the budget requested from the State of Hawaii.

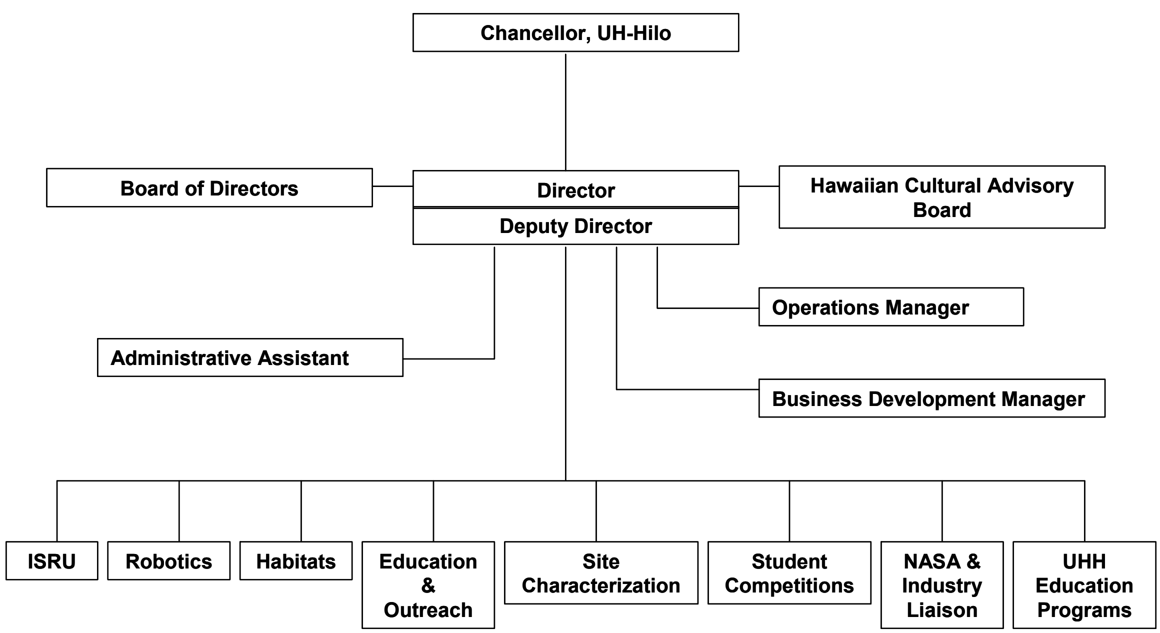

Figure 1. *PISCES Organization Chart*

d) <u>Providing resources to expand educational activities</u>. NASA Kennedy Space Center, one of the IPP partners, has agreed to provide funding in FY 2008 to bring three additional teams to the PISCES annual meeting to present their work on projects in ISRU technology development. The competition will be expanded to include business school teams that will be challenged to contribute to the definition of possible commercial projects built around space exploration and development or the operation of PISCES facilities. It is expected that Japanese teams, sponsored by Japanese organizations, will also enter the competition. Building on successful outreach efforts this year, and the establishment of the Hawaiian Cultural Advisory Board, PISCES will expand its education efforts in the Hilo K-12 schools and its outreach program to the local community. Goals of the PISCES education and outreach program are as follows:

- Build public awareness and support of PISCES.
- Attract, maintain and promote users/partners.
- Guide and support marketing, fundraising and government relations.
- Inspire the next generation of space scientists, engineers and technologists.

The model for PISCES is that of a university-government-industry partnership, which will expand the opportunities for conducting research and training within the PISCES framework. PISCES will identify topical areas that are consistent with the long-term development of the Center and seek teaming arrangements that can be supported through proposals to government, industry or private funding sources. As part of this effort, UHH will be encouraged to enter into cooperative agreements with other universities, such as is already being explored with the Colorado School of Mines, which has the nationally known Center for Space Resources.

e) <u>Offering PISCES courses at UHH</u>. The initial PISCES course being offered in the spring semester of 2008, "Topics in Space Sciences" with an emphasis on space exploration, will be offered again in FY 2008-09. In addition, other course offerings related to lunar outpost design and space exploration will be planned, which will form the backbone of an educational track in space exploration technology. Institution of such a track will be explored with the appropriate faculty governance groups at UHH.

f) <u>Evolving from State funding for PISCES toward sponsorship by industry or individuals</u>. This involves facility users providing the funding needed to carry out the research, education and field studies. This transition will require a dedicated effort to seek funding for capital improvements and endowed permanent staff positions. A professional fundraising organization will be employed in close coordination with those officials at UHH responsible for institutional advancement so as to avoid conflicts and ensure that the development of PISCES is of maximum benefit to the university. Any capital construction at UHH would most likely be located in the UHH Technology Park. A conceptual design of the permanent lunar outpost analog systems will be prepared. Based on requirements developed in the current fiscal year, a working group will be formed, consisting of government and industry personnel who will provide guidance to the outpost development. At the end of FY 2008-09 (June 2009) a summer study will be initiated in which professional architects, engineers and space technologists will address the PISCES requirements and develop design solutions that take into consideration both near term space agency plans as well as potential long-term futures for lunar habitats.

This group will also define the requirements for an architectural/engineering study for FY 2009-10 that will lead to a design for the permanent PISCES facility. PISCES will seek matching funds and in-kind contributions to support the summer study.

3. PISCES Innovative Partnership Program funded contract in Robotics: Development of Low-Temperature, Long-Life, Compliant Wheels for the Lunar Surface and Beyond

The success of the Mars Exploration Rovers has demonstrated the importance of mobility to planetary science and exploration. Increasing mobility will allow scientists to more readily explore environments and greatly expand mission flexibility. In order to achieve enhanced mobility, a long-life compliant wheel is needed which can function in extra-terrestrial environments. Compliance is essential in allowing lunar and planetary vehicles to move beyond the quasi-static speeds of MER (Mars Exploration Rover) into the dynamic regime required for joint human/robot operations, where impacts with small rocks would quickly destroy rigid wheels. Also, compliance allows the contact pressure to be nearly uniform, greatly reducing the rolling resistance for heavier vehicles. The rolling resistance grows roughly with the sinkange, thus the reduced sinkage of compliant wheels has a dramatic effect on rolling resistance. The Tweel (Time Magazine's 2005 Invention of the Year), designed by Michelin, is a non-pneumatic tire that has already demonstrated its effectiveness on the ATHLETE prototype lunar rovers developed by the Jet Propulsion Laboratory, as shown in Figure 2. Michelin has also developed a state-of-the-art technology that integrates glass fiber into vinyl ester to create a material that retains its superior elastic properties over the thermal range from boiling water to liquid nitrogen. This material can be used in the design of non-pneumatic compliant wheels capable of functioning in Lunar and Martian environments. These wheels will weigh less than current non-compliant designs while lasting far longer than other compliant alternatives in extreme conditions. Together, NASA's JPL, Michelin Americas Research and Development Center (MARC) and Clemson University have demonstrated initial feasibility of this technology for future space flight. Further development is needed to mature the design and to perform extensive analytical, laboratory and real world testing for validation. The result will be a wheel that is capable of meeting all of NASA's future mobility needs, such as those imposed by planned human and robotic precursor missions to the moon. This wheel shown in Figure 3 will be able to survive a traverse of planetary-scale distances while providing superior mobility performance to any current alternative. Two efficient compliant wheels have been developed for lunar surface operations. Based on the concept of the Michelin Tweel, these new wheel designs allow for a uniform ground pressure like a pneumatic tire, yet are constructed of materials that can endure a hard vacuum and intense ultra violet and atomic oxygen exposure without degrading. These wheels are designed for a long life and long traverses on the lunar surface, while maintaining a load carrying efficiency (Mwheel/Mvehicle) in excess of those developed for the Apollo LRV. Michelin has also developed a state-of-the-art technology that integrates glass fiber into vinyl ester to create a material that retains its superior elastic properties over the thermal range from boiling water to liquid nitrogen. This material can be used in the design of non-pneumatic compliant wheels capable of functioning in Lunar and Martian environments. These wheels will weigh less than current non-compliant designs while lasting far longer than other compliant alternatives in extreme conditions.

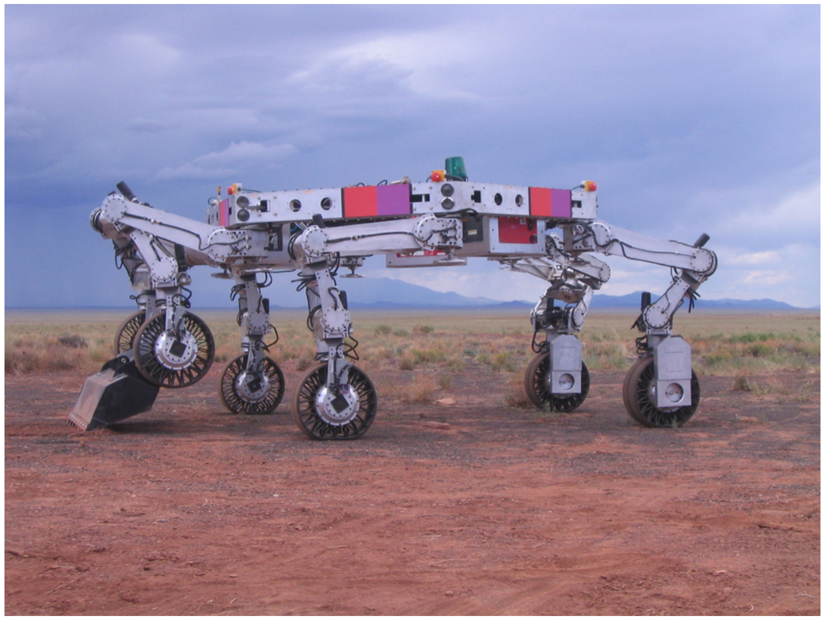

Figure 2: ATHLETE rover

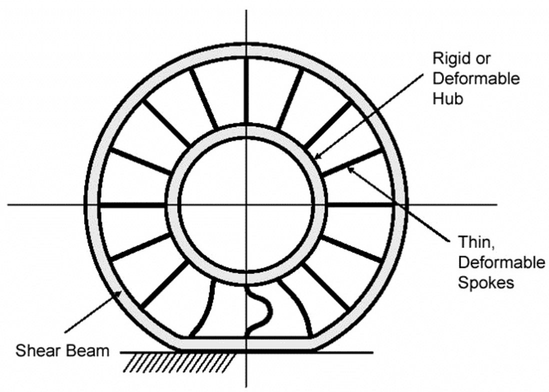

Figure 3. *The Tweel Concept*

Technical Approach: Wheels made to support NASA's intentions to return humans to the moon in the next decade must meet the following requirements:

- Operate in hard vacuum, high UV flux, and temperatures ranging from 40-400K
- Survive long durations (10 years) and distances (10,000 km) operating over lunar terrain at relatively high speeds (10kph)
- Have very high load carrying efficiency (mass of payload supported/mass of wheel)
- Be compliant & have low, relatively uniform ground contact pressure
- Have low rolling resistance and low energy loss from obstacle impacts
- Be non-pneumatic (immune to puncture and gas-law pressure/temperature variations, with shapes not necessarily limited by pressurized membrane shell mechanics)

If a wheel can be made to meet the above requirements, it will enable the vehicles supporting the lunar exploration program to travel distances approaching planetary scales. Such vehicles would be able to visit all of the sites deemed important for science or resources by the Exploration Systems Architecture Study (ESAS). Such a wheel would also be an important improvement over the rigid wheels presently used in the robotic exploration of Mars. Their compliance and low ground contact pressure would reduce the possibility of future rovers becoming trapped in soft soil (as happened with Opportunity in 2006). As a step towards meeting these requirements, a compliant, non-pneumatic, glass monofilament and resin composite wheel will be developed to survive at least 1000km on the lunar surface and be dynamically tested from 77 to 400K. It shall accomplish this while carrying a nominal load equivalent to 100 times its own weight in lunar gravity at speeds in excess of 10kph. These metrics represent a significant and necessary improvement over the Apollo LRV Wheel as seen in Table 1.

		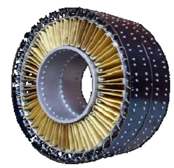	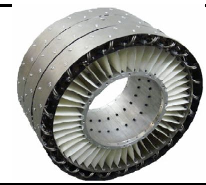	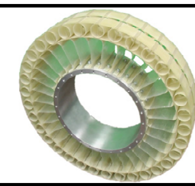
	Apollo LRV Wheel	**Clemson/JPL/Michelin Student Tweel**	**JPL Lunar Tweel**	**Composite Lunar Tweel**
Mass	**5.43 kg**	**8.2kg**	**4.7 kg**	**4 kg**
Max load	**400 kg**	**300 kg**	**400 kg**	**400 kg**
Load Carrying Eff.	**3%**	**3%**	**2%**	**1%**
Ground Pressure	**1psi**	**7.5psi**	**5psi**	**7psi**
Longest traverse	**120km**	**100km**	**500km**	**1000km**

Table 1. *Comparison of Lunar Non-pneumatic Wheel Designs*

Furthermore, the design and construction of this composite wheel is highly scalable and adaptable to varying design requirements, so it has the potential to become a sustainable solution for all extra-terrestrial mobility needs, providing higher reliable and efficient mobility over more types of terrain. The current development for lunar applications could readily be applied elsewhere to provide improved performance for any mobile system operating on other bodies of interest.

State of the Art: The Apollo LRV non-pneumatic wheels were each designed to survive a 20km traverse,

support a few hundred kilograms, and operate for a few days on the lunar surface. These wheels are known to have insufficient lifetime and load carrying capability to support NASA's new architectural requirements. While terrestrial tires have lifetimes in excess of 100,000km, the inherent limitations of elastomeric pneumatic tires in a lunar environment, such as risk of puncture, outgassing, UV and atomic oxygen degradation and hardening/brittleness at cryogenic temperatures make them inappropriate for a lunar mission. The most significant advance in wheel technology since Apollo has been the Michelin Tweel ® (Tweel=integrated tire & wheel). The Tweel is a non-pneumatic wheel that mimics the performance and advantages of pneumatic tires without the disadvantages of an integral pressure vessel. The ATHLETE Tweels have exceeded expectations but have several drawbacks which need to be addressed. Most importantly, the Tweels are comprised mostly of elastomer materials which, while suitable for terrestrial use, suffer from many of the same limitations as a pneumatic tire in a lunar environment. Additionally, they also contribute nearly 15% (12kgs) of the total mass of an ATHLETE limb

(90kgs), and nearly half of the wheel actuator assembly (28kgs). What is needed is a nonpneumatic wheel that has the performance and advantages of the Tweel, while being comprised of lightweight materials appropriate for launch into space. To this end, under ESMD funding, JPL, Michelin, and Clemson University have been collaborating on a 19” diameter lunar capable Tweel since mid 2006. This effort has culminated in the prototyping of an all-titanium tweel and an initial article of the composite Tweel identified for testing in Hawaii.

Because every vehicle on the road expends a portion of its fuel in overcoming rolling resistance, this technology could lead to a huge commercial market and advances in terrestrial fuel economy. In addition, there may be a small but important market for wheels that can withstand extremely hostile environments (nuclear plants, deep ocean, cold regions, hot regions, etc.) Clemson University will provide analysis, design guidance, and test support. This will mostly be provided by graduate students in the mechanical engineering department. JPL will host one or more of these students through the summer internship program and invite one of Hawaii Hilo University’s students to join the team. The Tweels will be subjected to real-world testing on a Carnegie Mellon-provided robot at the University of Hawaii’s Pacific International Space Center for Exploration Systems (PISCES) facility near the summit of the Mauna Kea Volcano. This site is thought to be one of the closest analogs to lunar terrain and, as such, was used in support of Apollo. PISCES will provide local infrastructure, test support, transportation and accommodations for the Tweel team. JPL and Michelin will produce a set of at least seven compliant wheels capable of surviving the entire lunar temperature range (40-400K). These wheels will be able to operate at speeds in excess of 10kph for at least 1000km in simulated lunar terrain. In addition to cold and hot chamber testing at JPL and endurance testing at Michelin, the wheels will also undergo real world testing on the ATHLETE lunar rover in other lunar analog terrain (JPL Mars Yard, Desert RATS and PISCES in the summer of 2008).

Benefits to NASA: If mobility of any kind is to be implemented on the moon, advanced wheels will be required. Because the expected duration of future lunar sorties is far longer than those of Apollo, robust, compliant wheels need to be developed. Because the Tweel design is easily scalable to virtually any size, loading requirements, or desired ground pressure, it will have immediate applicability to any number of planned extra-terrestrial missions involving surface mobility. The composite Tweel may be enabling if the Lunar Precursor & Robotic Program (LPRP) is to include any sort of mobility in the early part of the next decade before being infused into NASA’s mobile platforms in support of human lunar missions starting in 2019. In addition, the science community is no longer content with static landers being sent to the surface of Mars. Sojourner, the Mars Exploration Rovers and the upcoming Mars Science Laboratory all have rigid wheels. This presents a serious disadvantage when driving in soft soil as the wheel depends on sinking in order to support the vehicle weight, but the rolling resistance increases roughly with the square of the sinkage. By reducing rolling resistance, future rovers can consume less power than their rigid-wheeled predecessors. One disadvantage of rigid wheels was dramatically realized in the spring of 2006 when Opportunity became immobilized drift material. This incident caused the loss of more than a month of surface operations and many millions of dollars that could have otherwise gone to conducting surface science. In addition, by developing a compliant wheel that can also absorb impact loads so that traverse speed can be increased, allowing longer range science missions to be contemplated.

4. PISCES Innovative Partnership Program funded contract in *In-Situ* Resources Utilization: Evaluation of Space Material and Oxygen Production

The NASA Lunar Architecture Team recognized that *In-Situ* Resource Utilization (ISRU) resource prospecting and capabilities such as O=outpost site preparation and protection, oxygen production from regolith, *in-situ* water and fuel cell reagent production can provide significant mass and mission risk reduction benefits. However, since ISRU is an unproven capability, there is a significant need for performing integrated system tests in relevant environments to validate these benefits for architecture and mission planners. This is especially critical in relation to the development of technologies of interest to multiple projects (e.g. water electrolyzers) or the development of hardware and interfaces with other surface systems such as Power, Human-Robotic Systems (HRS), Extra-Vehicular Activity (EVA) and Life Support to obtain a complete surface capability (e.g., excavation requires an ISRU excavator end-effecter and a HRS surface mobility platform). Integrated field demonstrations are critical since they validate important surface system capabilities under realistic mission conditions (TRL 6) and demonstrate improvements in Capabilities (e.g., digging deeper); Performance (e.g., lower power); and Robustness (e.g., duration). Remote field demonstrations are also critical to identifying and understanding integration and joint operation issues and problems, as well as building relationships for design, data and hardware collaboration and exchange.

The Lunar Analog Field Demonstration project is a partnership between NASA and the University of Hawaii/State of Hawaii that will bring together technologies under development in Exploration Technology Development Program (ETDP) ISRU and HRS Projects at the lunar analog site under development by the Pacific International Space Center for Exploration Systems (PISCES) managed by the University of Hawaii-Hilo. Basing these field demonstrations in Hawaii, especially on/around the Mauna Kea volcano, will provide a superior lunar analog test environment for both HRS and ISRU hardware that must learn to operate on volcanic soils and process volcanic material. Mauna Kea is the ideal location for a test site for a number of reasons. During the Apollo program it was used as a training site for the astronauts who deemed it the most realistic analog site they trained on. Additional factors related to the site that make it ideal for realistic ISRU and HRS field testing are:

- Abrasive volcanic material with mineral composition that has similarities to lunar regolith
- Volcanic material and subsurface permafrost for lunar water prospecting system field testing
- High altitude for high quality sunlight for solar concentrators for regolith heating
- Existing testing, infrastructure and lodging facilities – minimizes travel and setup time

The joint ISRU/HRS lunar analog field demonstrations as depicted in Figure 4 will be based around important surface system capabilities or “Themes” to evaluate goals and characteristics associated with different surface operations that will likely be required for pre-Outpost and Outpost lunar surface operations. Themes currently under joint development by the ISRU and HRS Projects are: i) Prospecting/Site Surveying/Science; ii) Surface Manipulation for Outpost Emplacement and Safety; and iii) End-to-end Oxygen Extraction from Regolith.

While numerous analog field tests have been performed in the past, none of these have been aimed at developing and improving ISRU hardware and systems, and most of them have been aimed at simulating Mars surface operations and environments. The NASA/Hawaii project team proposes to develop a lunar analog site that will provide NASA an ideal location to conduct lunar hardware field validation tests for a multitude of ESMD projects. It will also advance the TRL of two enabling technologies that are an important part of the lunar architecture, ISRU and HRS. ISRU and HRS are interdependent technology projects that, as a result of this proposal, will have the opportunity to integrate hardware developed under ETDP funding for the first time. PISCES primary role will be to develop the test site infrastructure based on NASA requirements, freeing NASA from the long term cost of facility management. NASA ESMD projects will be able to return to the PISCES test site on an as-needed basis as a rental client for the remainder of the lunar program.

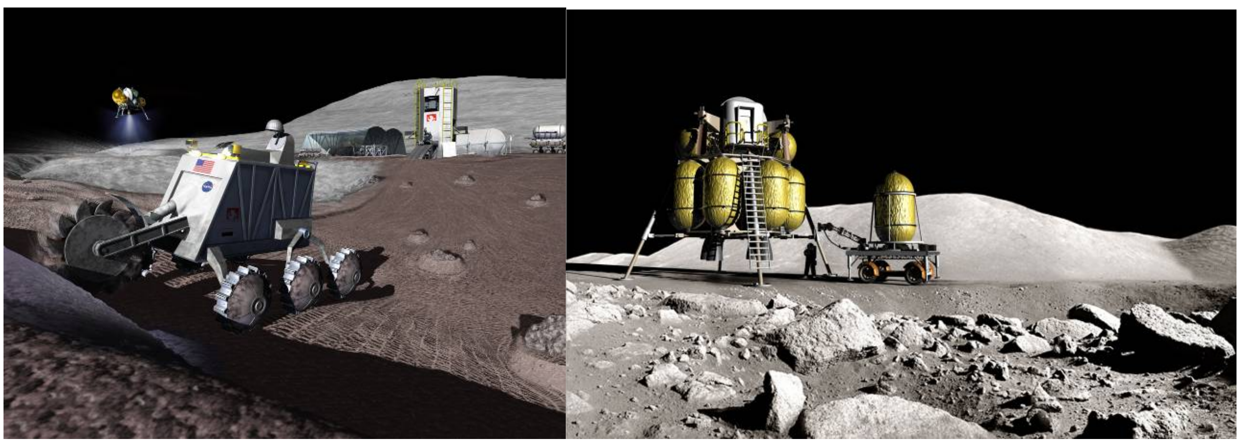

Figure 4. *Depiction of ISRU/HRS Lunar Analog Field Demonstration*

An effort will be made to coordinate additional instruments and/or surface platforms testing with Science Mission Directorate (SMD)/Ames Research Center (ARC) personnel for joint field testing. This activity will be coordinated with a possible IPP Seed Fund proposal between NASA and Hawaii through ARC ("Lunar Robotic Site Survey and Sampling"). Effort will also be made to coordinate additional instruments and remote operations with the Canadian Space Agency (CSA), especially in the area of vision system integration for drill site selection and remote operations through satellite communications.

While different aspects of ISRU resource prospecting and surface manipulation have been developed and field-tested in the past, truly relevant ISRU technologies and hardware have not been tested under appropriate lunar surface analog conditions. For oxygen extraction from regolith, only subsystem laboratory tests have been performed. For resource prospecting, NASA Science Mission Directorate has performed a number of field tests demonstrating drilling for subsurface sample acquisition and mobile site mineral, topography and subsurface characterization but not as an integrated system or operation and not with measurements aimed at resource characterization and processing in mind for ISRU. For surface manipulation, tests with various blades and scoopers have been performed with rovers and other mobile platforms (e.g., Desert Research and Technology Studies (Desert RATS) testing of blade and backhoe in 2005), but the tests have been aimed at developing and demonstrating robotic hardware operations and interaction with EVA astronauts. The hardware and platforms were not designed, built or tested to evaluate or improve ISRU hardware or operations. For Lunar Analog Sites, analog site field tests have been performed for years at other locations such as Meteor Crater in Arizona and Haughton Crater in northern Canada. The local material, topography and rock distribution of these sites are a good analog for Mars robotic science and human exploration but are not representative of lunar sites of interest. During the Apollo program, several analog sites were utilized, but the one deemed "most realistic" by astronauts after their mission was the Mauna Kea volcano site on Hawaii.

Technical Approach: Both the ISRU and HRS projects in ETDP are developing technologies, hardware and systems that are relevant to future robotic and human exploration of the Moon. For oxygen extraction from regolith and resource prospecting, an integrated package called RESOLVE (Regolith and Environment Science & Oxygen and Lunar Volatile Extraction) is under development by the ISRU project. RESOLVE includes a one-meter drill and sample transfer device, a crusher, an oven and gas chromatograph to quantify water and volatiles in the sample, and a high temperature reactor to extract oxygen from the soil using the hydrogen reduction process. In parallel, a surface mobility platform that can support integration and operation of the drill or complete RESOLVE package is under development by the Carnegie Mellon University (CMU) with support from the Glenn Research Center (GRC) under the HRS project. For surface manipulation, different methods of excavation and material transport are under development. In particular, a large articulated blade/scooper is under development by KSC in the ISRU project. In parallel, mobility platforms to carry crew and cargo are under development by the HRS project. As a part of this project, a crew rover that could support landing pad clearing and berm building under development by Johnson Space Center will be utilized. From the lunar analog site point of view, Mauna Kea has a long history that ties it to the space program. During Apollo several sites on the volcano were used for astronaut training activities. More recently, site surveys performed by Ames Research Center in June under a signed a Space Act Agreement with the State of Hawaii have identified several potential analog sites on the slopes of Mauna Kea. Even though sites were evaluated with respect to meeting future SMD goals and objectives, the information obtained is a good starting point for subsequent site evaluations. Also, experience from the Desert RATS team, who have successfully performed remote analog site field tests for robotic and EVA systems over the last several years, will be factored into the site selection and infrastructure development.

The Lunar Analog Field Demonstration project will involve four interrelated efforts: NASA ISRU and HRS ETDP projects will integrate, test, and modify hardware (currently under development by each project) in preparation for field testing. For ISRU, this involves development of the RESOLVE package and a blade/scooper. For HRS, this involves development of a prospecting rover by CMU and a crew transport platform by JSC. These units will be integrated and field tested locally before shipment to PISCES.

Lunar analog site selection, development and preparation for ISRU field testing will involve:

- Defining requirements for infrastructure and analog site needs by NASA. Requirement definition will involve members of the Desert RATS and Mars Haughton Project teams.

- Analog site selection by PISCES and NASA members through scouting and evaluating possible sites for ISRU testing. Samples of local material at these sites will be evaluated for subsurface permafrost for prospecting and compared to actual lunar regolith physical and mineral characteristics for oxygen extraction. PISCES will work with Hawaii cultural and government officials to define procedures for site access and operation.
- Infrastructure identification and buildup by PISCES, with NASA support, of existing infrastructure at the US Army base at Mauna Kea as well as astronomer dormitory facilities near the peak of Mauna Kea. Rent/buy decisions will be made by PISCES with consultation with NASA for near-term/long-term analog site test plans and needs. NASA and PISCES will perform field tests of Oxygen Extraction, Prospecting, and Surface Manipulation for Outpost capabilities under realistic lunar surface conditions. PISCES, with NASA, will perform Public Outreach through establishing, running, and judging a University ISRU Design competition aimed at studying and designing ISRU hardware and systems for a lunar Outpost with some hardware built and tested by students to validate their concept. NASA will also approve the objectives and goals of the competition. ISRU-KSC will coordinate the IPP effort between NASA ISRU, HRS, and PISCES due to their Project Management responsibilities for RESOLVE. ISRU & HRS projects in ETDP will develop hardware separately using ETDP funding and will integrate and test hardware under the IPP effort PISCES will develop suitable lunar analog sites for ISRU testing with support from NASA, including site material characterization (MSFC) NASA (ISRU & HRS) will perform lunar analog tests with support from PISCES. PISCES will lead the University Student ISRU Design Competition with NASA support.

All efforts and funding with PISCES will be through a Reimbursable Space Act Agreement with the PISCES-University of Hawaii, Hilo. Commercial involvement in blade/scoop design and testing, commercialization of oxygen production technologies by LMA and Orbitec, commercial spin-off of rover development capabilities to CMU or other entities, and infrastructure and lunar analog site development may result from this IPP. Other Space Agencies will also need lunar analog sites as they focus on the moon and their usage of . PISCES should lower costs to NASA.

Benefit to NASA: The IPP supports ESMD and ETDP in the following:

- Integration of ISRU/HRS surface system capabilities for Outpost to reach TRL 6.
- Development of high quality lunar analog site for ISRU and all other ESMD surface systems.
- Potential partnership with SMD and International Space Agencies (CSA). The IPP supports SMD goals and objectives.
- New Remote Sensing Technologies & Novel Platforms.

NASA Return on Investment (ROI) will be realized through relevant hardware development and demonstration and analog site development and use. Field demonstrations promote collaborative efforts and integration within ESMD and external partners. Funding from Hawaii will also be focused on NASA's needs and NASA support for PISCES will encourage further State support for analog site improvements. PISCES can also be utilized in subsequent years by NASA and costs further reduced to NASA if the same sites are used by other lunar hardware developers.

Summary

The State of Hawaii, by continuing funding the development of PISCES, will expand its active use and support by NASA, JAXA, their affiliated companies and other industries engaged in space commerce. Because Hawaii has stepped up to fund PISCES last year, it has attracted the attention of space professionals and organizations worldwide and played a major role in convincing NASA to award two Innovative Partnerships Program seed grants totaling more than its investment in support of PISCES. Continued funding from the State will ensure NASA and others that Hawaii is serious about its ambitions to be the space center of the Pacific Rim and will help PISCES to gain even more leverage in the coming years.

The State of Hawaii will benefit greatly through economic development, especially on the Big Island. By inspiring students to study STEM disciplines through the excitement of space exploration, PISCES will help create the future technical workforce that can attract additional high-tech industry and foster economic development throughout the State. Hawaii is a convenient location for participants from around the Pacific Rim and offers an unparalleled simulation environment for lunar and Martian surface operations. Hawaii's weather allows year-round operations in expansive areas of dry, barren terrain, with abundant sunlight for solar power. Hawaii can be reached in 5-10 hours from the continental US or 6-7 hours from Japan and many other countries on the Pacific Rim.

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